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Combatant Eye Protection: An Introduction to the Blue Light Hazard

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14. ABSTRACT

Introduction - Combat spectacles have successfully provided protection from penetrating ocular injury for over 5 years; the primary obstacle to their successful performance had been getting Soldiers to actually wear the protective gear. As success stories emerged (via photographic evidence), compliance rates approached 100%. The risk of functional eye injury resulting from visible solar radiation has been less obvious. Moreover, the risk of functional ocular tissue injury from LED-generated radiant energy remains under scrutiny. All LEDs (i.e., those embedded within digital tactical display systems, flat panel instrument displays, computer monitors, and televisions) can possess major energy outputs across the blue spectrum, independent of their apparent white or observational color. Methods - This report is based on current data-extrapolation from prior work that had quantified alterations in rabbit corneal metabolic activity secondary to in-vivo UV exposures. (Continued on next page)

15. SUBJECT TERMS

Functional eye injury, radiant energy (outdoor and indoor lighting), circadian clock, retinal pigment epithelium (RPE), age-related macular degeneration

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Abstract (continued)

Methods (continued) - For each UV wavelength used (290 nanometers [nm], 300 nm, 310 nm, and 360 nm), the exposures varied from 0.05 J/cm^2 to 0.25 J/cm^2 (in 0.05 J/cm^2 steps), based on the need to maintain environmental relevance. Micro-polarographic corneal oxygen uptake rates served as the *in-vivo* index of alteration in oxidative metabolic rate.

Results - A multi-factorial analysis of variance exhibited an overall significant between-groups effect by wavelength ($p < 0.0001$), as well as an interactive effect between wavelength and radiant energy dose ($p < 0.005$). Control eyes were stable. Extrapolation of the nonlinear trend lines out into visible wavelengths reached baseline near 447 nm.

Discussion - Evidence of metabolic vulnerability to visible light extending well into the blue spectrum is vitally important, as this is indicative of a moving, scalable effect, with no traditional threshold delineating expectation of damage/no damage. Added stressors (e.g., increased altitude or contact lens wear) could shift the wavelength effects toward a more damaging clinical picture. Recent reports have indicated rod photo-pigment damage resulting from solar blue-light exposures, adversely affecting unaided night vision, a militarily important performance decrement.

Conclusion - The incorporation of blue filters in conjunction with current protective eyewear represents one potentially proactive solution, but there are limits. A defined research program regarding establishment of human functional ocular parameter limits would be essential to overall safety. The activation wavelength for the daily synchronous setting of the Circadian Clock, which regulates the synchronization of all hormonal and organ systems throughout the bod, falls within the blue light perceptual range (at approximately 465 nm $^+/_-$ 5 nm). Thus, protection against blue light photo-damage cannot involve the application of a broadband or full-time blue filter application. Ideally, a narrow-band blue filter should be developed, preceded by an applied research program to ensure the safe application of this proposed new filtering capability.

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Introduction

Physical and UVR protection

Combat spectacles have successfully provided protection from penetrating ocular injury for over five years; the primary obstacle to the protective spectacle's successful performance had been getting Soldiers to actually wear the protective gear. As success stories emerged (via photographic evidence, Figure 1), compliance rates approached 100 percent. The risk of functional eye injury resulting from solar-based ultraviolet radiation (UVR) was less obvious, but clearly annotated over 30+ years of established environmentally-based ophthalmic research. (Pitts, 1959; Pitts and Tredici, 1971; Pitts, 1977; Sliney, 1983; Pitts, Bergmanson, and Chu, 1987; Pitts, 1993). Consequently, UVR protection is present in every pair of glasses developed or sold in America (both clear lenses and sunglasses), based on American National Standards Institute dictates (ANSI Z80.31); including the Army's new Transition Combat Eye Protection (TCEP) system, a developmental Soldier Survivability initiative of PEO Soldier (Figure 2). Nevertheless, the risk of functional ocular tissue injury from visible solar radiation (i.e., blue light), as well as from light-emitting diode (LED)-generated radiant energy remains a questionable factor under continued scrutiny.

Figure 1. Current protective goggle effectiveness. The soldier wearing these goggles in the photo to the left was obviously near the site of an Improvised Explosive Device (IED) explosion. Multiple peripheral facial wounds occurred during the attack. Small debris "spall" is embedded randomly across his face, as well as in the protective lenses. Without the protective spectacles, a similar embedded debris pattern would have certainly injured his eyelids, and potentially across the surface of both eyes, causing painful corneal foreign body injuries. Deep penetration into either or both eye(s) could potentially lead to loss of an eye.

Figure 2. Prototype protective goggle. The above photo is of a prototype of the Transition Combat Eye Protection (TCEP) system, a developmental Soldier Survivability initiative of PEO Soldier. The protective eyewear provides ballistic fragmentation protection as well as UV protection. However, there are no plans to incorporate any filters protective against the "blue light hazard." The lenses can adjust to varying light conditions with a one second response time. An easy 'fix' to the dilemma or gap identified by this paper would be to add a blue filter, particularly a narrow-band blue filter.

The Air and Space Interoperability Council (ASIC), a formal five nation military organization (the United States, the United Kingdom, Canada, Australia, and New Zealand), possesses a mandate to enhance coalition warfighting capability through air and space interoperability. ASIC seeks to promote interoperability through standardization across the spectrum of expeditionary warfare, as well as to share relevant information and technology. To that end, one aspect of sought-after standardization (which the U.S. Forces have yet to agree with) has been a recommendation incorporating a broad-band blue filter (with 0 percent transmittance from 400 to 500 nanometers (nm)) within both sun glasses and helmet visors. Clear spectacle lenses are to remain completely clear throughout the entire range of visible light without any blue filter protection, despite the strong filtering of all ultraviolet energy (The Air and Space Interoperability Council, 2014).

Methods and results

This research is based on current data-extrapolation from prior work that had quantified alterations in rabbit corneal metabolic activity secondary to in-vivo UVR exposures. For each UVR wavelength used (290, 300, 310, and 360 nm), the exposures varied from 0.05 J/cm^2 to 0.25 J/cm^2 (in 0.05 J/cm^2 steps), based on maintaining environmental relevance. Micro-polarographic corneal oxygen uptake rates served as the in-vivo index of alteration in oxidative metabolic rate. Analysis of variance exhibited an overall significant between-groups effect by wavelength ($p < 0.0001$), as well as by an interactive effect between wavelength and radiant energy dose ($p < 0.005$). Control eyes were stable. Extrapolation of the nonlinear trend lines outward into the visible wavelengths reached baseline at 447 nm, indicating the metabolic risk posed by exposure to 400 to 447 nm visible light.

Discussion

Issue #1

The above data extrapolation plot, extending beyond the longest UVR wavelength exposure (from 360 nm into the visible blue wavelength range) highlights a convergence of decreased oxygen utilization profiles, which unite at 447 nm. In concert, this indicates the capacity for blue light–induced photo-chemical damage to decrement corneal cellular metabolic performance (as evidenced by decreased oxygen consumption). This evidence of metabolic sensitivity to visible light extending well into the blue spectrum is vitally important, as the data are suggestive of a moving or scalable effect, with no traditional threshold establishment, which normally delineates the expectation of a damage/no damage cut-off point. Added stressors (e.g., increased altitude or contact lens wear) could shift the wavelength effects toward an even more damaging metabolic-associated clinical picture. Photoreceptor vulnerability to blue light (from both solar and LED sources) have been documented by several key investigators (Noell, 1980; Boulton et al., 1990; Boulton and Dayhaw-Barker, 2001; Behar-Cohen et al., 2011; Beatty et al., 2000).

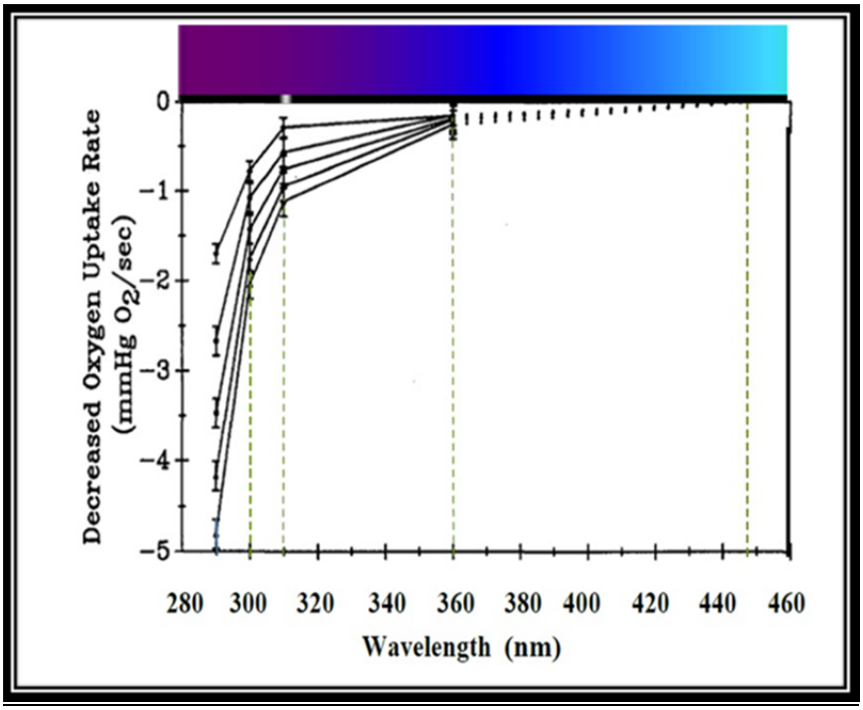

Figure 3. Data extrapolation indicating metabolic effect of visible light (esp. blue). The experimental effects of UVR on the corneal oxygen uptake rate were established at 290, 300, 310, and 360 nm, revealing a ‘family’ of curves as a function of wavelength and exposure energy. The five lines all converge to a wavelength of 447 nm, which is well within the blue range(s) of the visible spectrum, implying ophthalmic tissue metabolic vulnerability to this photochemical injury mechanism. The ‘colored’ bar at the top of the graph demonstrates the perceptual appearance of the respective wavelengths. The

above figure's current analysis and discussion are newly crafted and expanded. USAARL Technical Report 91-10, entitled: "Ultraviolet Radiation Effects on the Corneal Epithelium" was presented at the AGARD Aerospace Medical Panel Symposium on Ocular Hazards in Flight, and Their Remedial Measures, 22-26 October 1990, London, UK.

Issue #2

Noell (1980) found the retinal action spectrum of incident short wavelength light peaking at 457 nm, altering rhodopsin's molecular structure located within the rod photoreceptor outer segment. This rod photo-pigment damage resulting from solar blue-light exposures, will thus adversely affect unaided night vision, a performance decrement of vital operational importance to the military. Both longer wavelength exposures and longer duration exposures lead to overall photoreceptor structural damage, as well as secondarily related damage to the retinal pigmented epithelium (RPE). More recent research on RPE damage has indicated a direct link to eventual age-related macular degeneration (AMD), affecting the central visual field, capable of reducing visual acuity to the point of legal blindness (Margrain et al, 2004).

As new retinal photoreceptor outer segment discs are grown and inserted at the base of the outer segment 'stack', the outermost, oldest discs are shed daily upon initial light exposure (specifically activated by 470 nm blue light). This is a mammalian-specific, systemically-synchronous, Circadian event, occurring within the first hour after awakening (La Vail, 1976; Katz et al. 1982). The shed discs are then phagocytized by the surrounding RPE. Consequently, this access to blue light at 470 nm wavelength in the initial hour after awakening is an absolute necessity for continued physiological well-being of the retina. Renewal of the photosensitive outer segment of rod visual cells involves the continued assembly of new membranous discs, accompanied by a balanced loss and destruction of old disc material. The repeated formation of new discs serves to displace older discs away from the assembly site, towards the apex of the outer segment (Young, 1971). Discs are shed from the end of the cylindrical rod segment in groups generally containing 8 to30 discs. The endmost discs curl up at the edge, displacing a small amount of cytoplasm into the space thereby created. The outer rod membrane then folds into the zone separating the deformed discs from the remainder of the outer segment. This serves to dissect away the terminal discs while reforming the membrane over the tip of the cell. Next, the shed discs are surrounded by cytoplasmic extensions from the RPE, subsequently withdrawn into the body of the tissue layer within a phagosome, where the material is enzymatically digested into sequentially smaller molecules, concluding with complete absorption (Hall and Bok, 1974).

Light absorbing materials within the RPE (such as melanin, lipofuscin and retinoids) make them susceptible to photochemical damage as a result of their absorption spectra. Lipofuscin, a conglomerate of modified lipids and bis-retinoids, accumulates with age in the lysosomes of the RPE as a by-product of the normal visual Circadian cycle's phagocytosis (i.e., outer segment shedding occurring every morning on initial light exposure) (Bazan, 2006; Yalin et al., 2014; Sparrow et al., 2010). The most studied by-product of this retinal cellular digestive process is lipofuscin (Ben-Shabat, 2002; Sparrow, Nakanishi, and Parish, 2000). Lipofuscin is highly photo-oxidative in response to blue light, generating a reactive singlet oxygen (Kim et al., 2006).

Morgan et al. (2008) have observed unexpected retinal changes following blue light exposures, detecting long-term disruption of the RPE mosaic. These findings confirm a combined blue light-RPE linkage in the gradual development of age-related macular degeneration. AMD is the leading cause of blindness in the developed world and currently affects 12.7 million people in Europe and North America (Klein et al., 2014; Marshall, 1985). AMD can be either a gradual loss of central vision over a period of months to years, or an acute process, evidenced in only a matter of weeks. Both processes eventually result in an absolute central scotoma, characterized by a central area of absolute vision loss. The underlying processes leading to AMD is RPE age-related vulnerability, leading to decreased reactivity. The RPE cells are retained throughout life, with their repair systems operating at a molecular level (Klein et al., 2004).

Cumulative photoreceptor outer segment injury from chronic blue wavelength exposures contributes to a decline in RPE melanin content, associated with advancing years, which is also accompanied by an increase in RPE lipofuscin content causing a rising tide of cellular photo-stress. Lipofuscin is a potent generator of reactive oxygen species (ROS), exhibiting a further inhibitory effect on antioxidant activity (Boulton, et al. 1993). In summation, the chronology of lipofuscin accumulation in the RPE is coincident with the development of AMD (Feeney-Burns, Hildebrand, and Eldridge, 1984), with the photo-toxicity contributed by lipofuscin increasing substantially with age. A number of population-based studies have evaluated the role of UV and visible light in the development of AMD (Cruickshanks et al., 1997; Darzins, Mitchell, and Heller, 1992; Hyman, Cramer, and Rownd, 1982; Taylor et al., 1992; West et al., 2011). An extensive survey of the watermen in the Chesapeake Bay area concluded that chronic exposure to blue or visible light may be related to the development of AMD, as well (Bressler et al., 1989). Similarly, the authors of the Beaver Dam Eye Study also suggest that their measures indicate that visible light rather than UV might be associated with AMD (Cruickshanks et al., 1997). Conversely, Darzins et al. in their Eye Disease Case Control Study Groups (1992; 1997) found no such relationship (Darzins, Mitchell, and Heller, 1997a; Darzins, Mitchell, and Heller, 1997b).

Issue #3

The objectives of protection are to block or at least mitigate acute and chronic exposure effects, as well as to limit the risks of late-developing effects. Protection standards are the results of empirical approaches to various problems reflecting current qualitative and quantitative knowledge. Epidemiological experts have long ago demonstrated the risks of cataract development in those individuals involved primarily in outdoor professions. Increasingly relevant to those concerns are the risks posed to everyone for retinal degeneration: from ultraviolet radiation; from thermal injury processes; and from visible, white LEDs. The LED spectral distribution in the Figure 4 reveals major spectral output peaks at or slightly below 400 nm, dipping into the near UVR range.

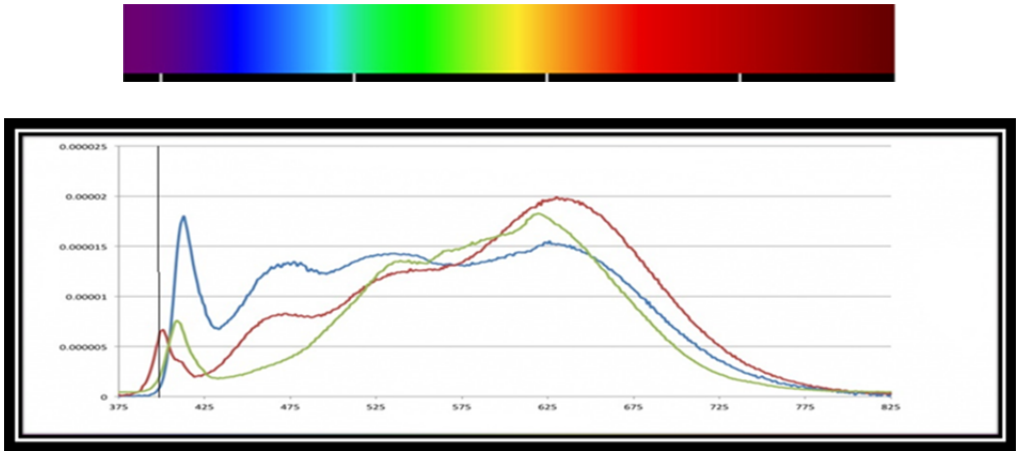

Figure 4. Example of the underlying spectral output of a very bright white LED. The 400 nm wavelength LED can shift slightly, changing the relative concentrations of red, green, and blue phosphors (annotated by the color of line used). The output from these new LEDs (with a very strong blue and near ultra-violet energy output) produce lighting that is extremely bright, making them ideal for airfield marking lights, or even for medical imaging or spectroscopy (extracted from open-photonics.com).

Extended retinal exposures to visible blue light at wavelengths below 550 nm produced actinic or photochemical effects at retinal wavelengths and irradiancies too low to produce thermal effects (Friedman and Kuwabara, 1968; Harwerth and Sperling, 1984; Lawwill, Crockett, and Currier, 1977). However, there is no sharp line of demarcation between thermal and actinic effects. Furthermore, there is a region where thermally enhanced actinic effects can occur. The action spectrum for actinic effects in the retina increases exponentially as the wavelength is decreased toward 400 nm (Ham et al., 1980). Importantly, these energy distribution curves are becoming increasingly relevant to our daily lives, as a result of their use in mobile phones, modern televisions, computer monitors, tablets, and flat panel display technologies (items commonly viewed on a daily basis for hours). As a further impetus for caution, an interactive damage zone has been demonstrated to reside in the retina, ranging from 450 to 550 nm. In which case, both thermally-enhanced and photo-chemical effects can occur in individuals with a genetic predisposition to these injuries. The process occurs on an interactively magnified basis, inducing greater tissue injury than either mechanism acting alone. Proteomic and genomic analyses will be needed to develop a practical injury mitigation strategy for those sensitive to this process.

Issue #4

Beyond the three primarily accepted photoreceptors within the retina, there is a fourth photoreceptor type, which is actually a directly photosensitive ganglion cell, different from the ganglion cells of the visual perception system. Its internal receptor has been termed melanopsin, partly due to its underlying vitamin A infrastructure, which is common to the other three retinal photoreceptor types. Matsuyama et al. (2012) reviewed the photochemical properties of mammalian melanopsin. Melanopsin was shown to serve as the input for various nonvisual

behavior and physiological functions. The nonvisual photoreceptor melanopsin absorbs blue light and triggers the biological clock of mammals by activating the suprachiasmatic nuclei (a small region of the brain that regulates the Circadian rhythm of neuronal and hormonal activities over 24-hour cycles), synchronizing the animal's innate Circadian rhythm to the solar light-dark cycle. The setting of the Circadian clock affects every cell and organ/tissue in its initial daily activation; from that point on, each cell/system/tissue runs its own clock throughout the next 24 hours, in isolation from all the other tissues, resynchronizing the next morning. Circadian clock or Circadian rhythm asynchrony has been hypothesized as a primary underlying basis for broad-based systemic disease.

A comprehensive spectroscopic study of melanopsin's photochemical properties, has shown an absorption maximum at 467 nm, which is chemically converted to a meta-intermediate having an absorption maximum at 476 nm. Sekharan, Wei, and Batista further noted photo-conversion of the meta-state back to the native melanopsin structure occurs via exposure to longer wavelength yellow and red light (2012). These photochemical properties suggest that a single site mutation could convert these nonvisual sensory photoreceptors into visual light sensors, or vice-versa. This observation holds relevance to color sensitivity-testing anomalies, which do not always readily segregate themselves into discretely established color vision categories, complicating any attempts at color vision testing standardization.

Optical filters designed to absorb incident blue wavelengths have been developed as strictly broadband filters (blocking transmittance of 400 to 500 nm wavelengths). Commercially-available blue-blocking lenses (also known as blue-blockers; shooting glasses; or yellow, scattered-light blockers), not only interfere with the initial morning triggering of the Circadian clock via melanopsin absorption, but also severely disrupt color identification as well as image analysis (McLean, Rash, and Schmeisser, 2000). Both the military and the general public has persisted in its perception that viewing through such lenses will improve overall visual sensitivity, thereby enhancing visual performance. This impression was first noted within the scientific literature as early as 1915 (Luckiesh, 1915) having subsequently been investigated numerous times within the DoD (Allen, 1961; Dobbins and Kindick, 1965; Kislin et al., 1968; Richards, 1973; Whitman, 1973; Kinney et al., 1980; Kinney and Luria, 1983; Luria, Wong, and Rodriquez, 1983; Provines, et al., 1983; Dees and Lyle, 1989; Provines et al. 1992; Thomas, 1994; Rabin and Wiley, 1996; Boff and Lincoln, 1998; Kodak, 1990; Schott Glass Technologies, Inc., 1998; Chung and Pease, 1999; Heikens, 1995; Rieger, 1992; Kuyk and Thomas, 1990; Aamisalo, 1988; Aamisalo, 1987; Kelly, Goldberg, and Banton, 1984; Corth, 1985; Yap, 1984; Richards, 1973; Bierman, 1952; Ross, 1950; Licina and Vosine, 1995; Richards, 1953; Richards, 1964; Davey and Seridan, 1953; Department of Defense, 1990), failing to demonstrate any broad benefit beyond that for one specific, limited condition.

Filters that attenuate blue light will have a beneficial effect in terms of retinal photo-protection, but may have unwanted side effects. For example, the action spectra for photo-sensitive ganglion cells, that are thought to have a role in setting our circadian clock, peak at between 467 and 484 nm (Sekharan, Wei, and Batista, 2012; Berson, Dunn, and Takao, 2002; Wolf, 2002). Consequently, it is possible that blue light filters may disrupt sleep cycles. However, sleep disruption has been reported in people who are 'blind', so the effect of the blue light filters is unlikely to be dramatic (Tabandeh et al., 1998). The ideal absorption

characteristics of sunglasses or intraocular lenses have not yet been established (Mainster and Sparrow, 2003). Current absorption filters are characteristically broad-band in nature, and do not possess the narrow-band characteristics necessary to be an effective protective method without bringing in side effects secondary to their broad-band nature.

Margrain et al. concluded in their review paper on this topic that there are now three compelling reasons for under-taking a large-scale clinical trial to evaluate the prophylactic effects of blue light filtration in AMD (2004). Firstly, there are now sound reasons for suspecting that blue light exposure in old age may contribute to the development of AMD. Secondly, the debate on the role of blue light exposure and AMD has continued for almost three decades, only a large-scale randomized clinical trial will have sufficient power to provide conclusive evidence. Thirdly, even a modest beneficial effect is likely to be associated with substantial individual and socio-economic benefits because AMD is reaching epidemic proportions, both here and in the UK (Evans and Wormald, 1996; Organisciak and Vaughan, 2010; Hafezi et al., 1997).

Conclusion

There is no single solution to all the delineated issue/problem statements. Suggested alternative solutions to the articulated problems involve a combination of potential actions:

1. Provide a recommendation that protective spectacle sunglasses and tinted visors include currently available broad-band blue-blocking component (400 to 480 nm) to supplement current UV-blocking technology (which is concurrently an ASIC Standardization recommendation), leaving all other optical corrective devices unchanged, until very narrow-band blue filters are developed.
2. Suggest a funding initiative in support of an optical engineering development of very narrow-band blue filters for use in all optical corrective devices (such that blue wavelengths from 400 to 450 nm are blocked, but exposures above 450 nm are fully transmitted).
3. Commission basic research to more closely evaluate the underlying mechanisms of the highly interactive solar and LED-generated wavebands. Artificially-induced cell death (or apoptosis) widely occurs upon wavelength-specific illumination from 400 to 450 nm, which is pre-disposed to causing actinic photoreceptor damage; as well as RPE damage by a combination of actinic and thermal interactive damage processes, resulting in elevated RPE changes and retinal degeneration. Protection against blue light photo-damage effects must defer to the daily requirement for the synchronously daily re-setting of the body's Circadian clock, until the ramifications of full-time, very narrow-band blue filters are fully understood.

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